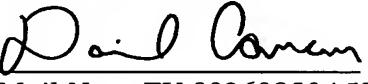


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MAGNETIC RECORDING MEDIUM AND
MAGNETIC STORAGE APPARATUS

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MAGNETIC RECORDING MEDIUM AND MAGNETIC
STORAGE APPARATUS

1 BACKGROUND OF THE INVENTION

2 This application claims the benefit of a
3 Japanese Patent Application No.2001-272601 filed
4 September 7, 2001, the disclosure of which is hereby
5 incorporated by reference.

6 1. Field of the Invention

7 The present invention generally relates to
8 magnetic recording media and magnetic storage
9 apparatuses, and more particularly to a magnetic
10 recording medium which is suited for high-density
11 recording and capable of carrying out high-speed
12 recording and reproduction, and to a magnetic
13 storage apparatus which uses such a magnetic
14 recording medium.

15 2. Description of the Related Art

16 Due to the developments in information
17 processing technology, there are increased demands
18 for high-density magnetic recording media. For
19 example, for a hard disk, the magnetic recording
20 media required to satisfy such demands should
21 include such characteristics as low noise and
22 improved thermal stability.

23 The recording density of longitudinal
24 magnetic recording media, such as magnetic disks,
25 has been increased considerably due to the reduction

1 of medium noise and the development of
2 magnetoresistive and high-sensitivity spin-valve
3 heads. A typical magnetic recording medium is
4 comprised of a substrate, an underlayer, a magnetic
5 layer, and a protection layer which are successively
6 stacked in this order. The underlayer is made of Cr
7 or a Cr alloy, and the magnetic layer is made of a
8 Co alloy.

9 Various methods have been proposed to
10 reduce the medium noise. For example, Okamoto et
11 al., "Rigid Disk Medium For 5 Gbit/in² Recording",
12 AB-3, Intermag '96 Digest, proposes decreasing the
13 grain size and size distribution of the magnetic
14 layer by reducing the magnetic layer thickness by
15 the proper use of an underlayer made of CrMo. U.S.
16 Patent No. 5,693,426 proposes the use of an
17 underlayer made of NiAl. Further, Hosoe et al.,
18 "Experimental Study of Thermal Decay in High-Density
19 Magnetic Recording Media", IEEE Trans. Magn. Vol.33,
20 1528 (1997), for example, proposes the use of an
21 underlayer made of CrTiB. The underlayers described
22 above also promote c-axis orientation of the
23 magnetic layer in a plane which increases the
24 remanence magnetization and the thermal stability of
25 the written bits. In addition, proposals have been
26 made to reduce the thickness of the magnetic layer,
27 to increase the resolution or to decrease the width
28 of the transition between written bits. Furthermore,
29 proposals have been made to decrease the exchange
30 coupling between grains by promoting more Cr
31 segregation in a magnetic layer which is made of the
32 CoCr alloy.

33 However, as the grains of the magnetic
34 layer become smaller and more magnetically isolated
35 from each other, the written bits become unstable
36 due to thermal activation and to demagnetizing
37 fields which increase with linear density. Lu et
38 al., "Thermal Instability at 10 Gbit/in² Magnetic

1 Recording", IEEE Trans. Magn. Vol.30, 4230 (1994)
2 demonstrated, by micromagnetic simulation, that
3 exchange-decoupled grains having a diameter of 10 nm
4 and the ratio $K_u V/k_B T \sim 60$ in 400 kfci di-bits are
5 susceptible to significant thermal decay, where K_u
6 denotes the magnetic anisotropy constant, V denotes
7 the average magnetic grain volume, k_B denotes the
8 Boltzmann constant, and T denotes the temperature.
9 The ratio $K_u V/k_B T$ is also referred to as a thermal
10 stability factor.

11 It has been reported in Abarra et al.,
12 "Thermal Stability of Narrow Track Bits in a 5
13 Gbit/in² Medium", IEEE Trans. Magn. Vol.33, 2995
14 (1997), that the presence of intergranular exchange
15 interaction stabilizes written bits, as demonstrated
16 by MFM studies of annealed 200 kfci bits on a 5
17 Gbit/in² CoCrPtTa/CrMo medium. However, more grain
18 decoupling is essential for recording densities of
19 20 Gbit/in² or greater.

20 The obvious solution has been to increase
21 the magnetic anisotropy of the magnetic layer. But
22 unfortunately, the increased magnetic anisotropy
23 places a great demand on the head write field which
24 degrades the "overwrite" performance, which is the
25 ability to write over previously written data.

26 In addition, the coercivity of thermally
27 unstable magnetic recording medium increases rapidly
28 with decreasing switching time, as reported in He et
29 al., "High Speed Switching in Magnetic Recording
30 Media", J. Magn. Magn. Mater. Vol.155, 6 (1996), for
31 magnetic tape media, and in J. H. Richter, "Dynamic
32 Coercivity Effects in Thin Film Media", IEEE Trans.
33 Magn. Vol.34, 1540 (1997), for magnetic disk media.
34 Consequently, adverse effects are introduced in the
35 data rate, that is, how fast data can be written on
36 the magnetic layer and the amount of head field
37 required to reverse the magnetic grains.

1 On the other hand, another proposed method
2 of improving the thermal stability increases the
3 orientation ratio of the magnetic layer by
4 appropriately texturing the substrate under the
5 magnetic layer. For example, Akimoto et al.,
6 "Relationship Between Magnetic Circumferential
7 Orientation and Magnetic Thermal Stability", J. Magn.
8 Magn. Mater. (1999), in press, report through
9 micromagnetic simulation that the effective ratio
10 $K_uV/k_B T$ is enhanced by a slight increase in the
11 orientation ratio. This further results in a weaker
12 time dependence for the coercivity which improves
13 the overwrite performance of the magnetic recording
14 medium, as reported in Abarra et al., "The Effect of
15 Orientation Ratio on the Dynamic Coercivity of Media
16 for >15 Gbit/in² Recording", EB-02, Intermag '99,
17 Korea.

18 Furthermore, keepered magnetic recording
19 media have been proposed for thermal stability
20 improvement. The keeper layer is made up of a
21 magnetically soft layer that is parallel to the
22 magnetic layer. This soft layer can be disposed
23 either above or below the magnetic layer. Oftentimes,
24 a Cr isolation layer is interposed
25 between the soft layer and the magnetic layer. The
26 soft layer reduces the demagnetizing fields in the
27 written bits on the magnetic layer. However,
28 coupling the magnetic layer to a continuously-
29 exchanged coupled soft layer defeats the purpose of
30 decoupling the grains of the magnetic layer. As a
31 result, the medium noise increases.

32 In order to improve the thermal stability
33 and to reduce the medium noise, magnetic recording
34 media and magnetic storage apparatuses have been
35 proposed in U.S. Patent Application S.N.09/425,788
36 filed October 22, 1999, which is incorporated herein
37 by reference, and in which the assignee is the same
38 as the assignee of this application. This

1 previously proposed magnetic recording medium is
2 comprised of at least one exchange layer structure,
3 and a magnetic layer formed on the exchange layer
4 structure, wherein the exchange layer structure
5 includes a ferromagnetic layer and a non-magnetic
6 coupling layer provided on the ferromagnetic layer
7 and under the magnetic layer, and the ferromagnetic
8 layer and the magnetic layer have antiparallel
9 magnetizations. According to this previously
10 proposed magnetic recording medium, it is possible
11 to improve the thermal stability of the written bits,
12 reduce the medium noise, and realize a high-density
13 recording having a high reliability without
14 adversely affecting the performance of the magnetic
15 recording medium.

16 In other words, in this previously
17 proposed magnetic recording medium, the non-magnetic
18 coupling layer (or the non-magnetic exchange layer)
19 is interposed between the ferromagnetic layer that
20 forms a first magnetic layer and the magnetic layer
21 that forms a second magnetic layer. When the
22 structure includes first and second magnetic layers
23 having antiparallel magnetizations, the first and
24 second magnetic layers mutually cancel portions of
25 the magnetizations. Hence, it is possible to
26 increase the effective grain size of the magnetic
27 layer without substantially affecting the resolution.
28 Therefore, from the point of view of the grain
29 volume, it is possible to increase the apparent
30 thickness of the magnetic layer so as to realize a
31 magnetic recording medium having a good thermal
32 stability.

33 Accordingly, this previously proposed
34 magnetic recording medium employs a basic structure
35 made up of the ferromagnetic layer (the first
36 magnetic layer) and the magnetic layer (the second
37 magnetic layer), so as to improve the thermal
38 stability and to reduce the medium noise.

1 When an external recording magnetic field
2 is applied to this previously proposed magnetic
3 recording medium, the first and second magnetic
4 layers first assume parallel magnetizations, and
5 when the recording magnetic field decreases to zero
6 (residual magnetization state) thereafter, the
7 magnetization of the first magnetic layer is
8 switched and becomes antiparallel to the
9 magnetization of the second magnetic layer.

10 However, as the recording density and the
11 signal transfer rate increase, it becomes necessary
12 to also increase the recording and reproducing speed.
13 For this reason, the need to wait for the switching
14 of the magnetization to occur in the first magnetic
15 layer after recording may interfere with the
16 realization of high-speed recording and reproduction.

17 In other words, the first and second
18 magnetic layers of this previously proposed magnetic
19 recording medium assume antiparallel magnetizations
20 in the residual magnetization state, and when the
21 external recording magnetic field is applied in this
22 state, the first and second magnetic layers assume
23 parallel magnetizations. Then, when the recording
24 magnetic field thereafter decreases to zero to
25 assume the residual magnetization state once again,
26 the magnetization of the first magnetic layer is
27 switched to become antiparallel to the magnetization
28 of the second magnetic layer. During this process,
29 it is necessary to wait for the first magnetic layer
30 to naturally make the magnetization switch.

31 But when the recording speed is increased
32 and recording to an adjacent bit is made before the
33 first magnetic layer makes the magnetization switch,
34 the position of the bit which is to be recorded may
35 shift due to a counter magnetic field from the bit
36 in the parallel magnetization state. In this case,
37 a non-linear transition shift (NLTS) deteriorates,
38 and adversely affects the recording.

1 On the other hand, when measures are taken
2 to reduce the time from recording to reproduction,
3 an abnormal signal is generated to prevent normal
4 reproduction if the reproduction is carried out
5 before the first magnetic layer is switched to the
6 antiparallel magnetization state from the parallel
7 magnetization state.

8

9 SUMMARY OF THE INVENTION

10 Accordingly, it is a general object of the
11 present invention to provide a novel and useful
12 magnetic recording medium and magnetic storage
13 apparatus, in which the problems described above are
14 eliminated.

15 Another and more specific object of the
16 present invention is to provide a magnetic recording
17 medium which has first and second magnetic layers
18 with antiparallel magnetizations to realize improved
19 thermal stability and reduced medium noise, and that
20 is capable of carrying out magnetic recording and
21 reproduction at a high speed, and to provide a
22 magnetic storage apparatus which employs such a
23 magnetic recording medium.

24 Still another object of the present
25 invention is to provide a magnetic recording medium
26 comprising a first magnetic layer, a second magnetic
27 layer, and a non-magnetic coupling layer provided
28 between the first and second magnetic layers so that
29 the first and second magnetic layers are exchange-
30 coupled and magnetizations of the first and second
31 magnetic layers are antiparallel, where the first
32 magnetic layer has an exchange coupling field H_{ex1}
33 which is larger than respective coercivities H_{c1} and
34 H_{c2} of the first and second magnetic layers.
35 According to the magnetic recording medium of the
36 present invention, the magnetizations of the first
37 and second magnetic layers can be maintained
38 antiparallel in a residual magnetization state, and

1 it is possible to realize a high recording density
2 and high-speed recording and reproduction.

3 A switching field H_{sw}^* which switches the
4 magnetization of the first magnetic layer to become
5 parallel to the magnetization of the second magnetic
6 layer may be set to a sum of the exchange coupling
7 field H_{ex1} and the coercivity H_{c1} of the first
8 magnetic layer. In this case, it is possible to set
9 a recording field within a range which does not
10 reach the level of the switching field H_{sw}^* , so that
11 it is possible to positively realize a magnetic
12 recording medium in which the magnetizations of the
13 first and second magnetic layers are rotated while
14 maintaining antiparallel magnetizations of the first
15 and second magnetic layers.

16 A magnetization and thickness product
17 $t_1 M_{s1}$ of the first magnetic layer is preferably
18 smaller than a magnetization and thickness product
19 $t_2 M_{s2}$ of the second magnetic layer, where t_1 denotes
20 a thickness of the first magnetic layer, M_{s1} denotes
21 a magnetization of the first magnetic layer, t_2
22 denotes a thickness of the second magnetic layer,
23 and M_{s2} denotes a magnetization of the second
24 magnetic layer. In this case, it is possible to
25 increase the exchange coupling field H_{ex1} of the
26 first magnetic layer having a small magnetization
27 and thickness product $t_1 M_{s1}$, so that it is possible
28 to more positively realize a magnetic recording
29 medium in which the exchange coupling field H_{ex1} is
30 larger than the coercivities H_{c1} and H_{c2} of the
31 first and second magnetic layers.

32 The coercivity H_{c1} of the first magnetic
33 recording medium is preferably smaller than the
34 coercivity H_{c2} of the second magnetic recording
35 medium. In this case, it is possible to determine a
36 main-sub relationship of the first and second
37 magnetic layers. In other words, it is possible to
38 design a magnetic recording medium in which the

1 second magnetic layer, which is set to have the
2 large coercivity $Hc2$, is used as the main recording
3 layer.

4 The magnetic recording medium may further
5 comprise a coupling intensifying region, provided
6 near the boundary of the non-magnetic coupling layer
7 and at least one of the first and second magnetic
8 layers, for intensifying the exchange coupling
9 strength between the first and second magnetic
10 layers. Further, the coupling intensifying region
11 may be made of a material selected from a group
12 consisting of Fe, Co, Ni and alloys thereof. With
13 the coupling intensifying region, it is possible to
14 obtain an exchange coupling field Hex which further
15 increases the exchange coupling between the first
16 and second magnetic layers.

17 A further object of the present invention
18 is to provide a patterned medium comprising a
19 recording surface, and a plurality of unit recording
20 portions, provided on the recording surface, having
21 boundaries which are separated among adjacent unit
22 recording portions. Each of the plurality of unit
23 recording portions preferably has a stacked
24 structure comprising a first magnetic layer, a
25 second magnetic layer, and a non-magnetic coupling
26 layer provided between the first and second magnetic
27 layers so that the first and second magnetic layers
28 are exchange-coupled and magnetizations of the
29 first and second magnetic layers are antiparallel,
30 where the first magnetic layer has an exchange
31 coupling field $Hex1$ which is larger than respective
32 coercivities $Hc1$ and $Hc2$ of the first and second
33 magnetic layers. According to the patterned medium
34 of the present invention, it is possible to realize
35 a high recording density and high-speed recording
36 and reproduction.

37 Another object of the present invention is
38 to provide a magnetic storage apparatus comprising

1 at least one magnetic recording medium, and at least
2 one head for applying a field to the magnetic
3 recording medium, where the magnetic recording
4 medium comprises a first magnetic layer, a second
5 magnetic layer, and a non-magnetic coupling layer
6 provided between the first and second magnetic layers
7 so that the first and second magnetic layers are
8 exchange-coupled and magnetizations of the first
9 and second magnetic layers are antiparallel, and the
10 first magnetic layer has an exchange coupling field
11 H_{ex1} which is larger than respective coercivities
12 H_{c1} and H_{c2} of the first and second magnetic layers.
13 According to the magnetic storage apparatus of the
14 present invention, it is possible to realize high
15 recording density and high-speed recording and
16 reproduction.

17 The field from the head may be larger than
18 a coercivity H_{c2} of the second magnetic layer and
19 smaller than a switching field H_{sw^*} which switches
20 the magnetization of the first magnetic layer to
21 become parallel to the magnetization of the second
22 magnetic layer. Moreover, the switching field H_{sw^*}
23 may be set to the sum of the exchange coupling field
24 H_{ex1} and the coercivity H_{c1} of the first magnetic
25 layer. In these cases, it is possible to positively
26 realize the high-speed recording.

27 Other objects and further features of the
28 present invention will be apparent from the
29 following detailed description when read in
30 conjunction with the accompanying drawings.

31 BRIEF DESCRIPTION OF THE DRAWINGS

32 FIG. 1 is a cross-sectional view showing
33 the main parts of one embodiment of a magnetic
34 recording medium according to the present invention;

35 FIG. 2 is an enlarged cross-sectional view
36 showing the main parts of a modification of the FIG.
37 1 embodiment of the magnetic recording medium;

1 FIG. 3 is a diagram showing a hysteresis
2 loop of the FIG. 2 modification of the magnetic
3 recording medium;

4 FIGS. 4A and 4B respectively are diagrams
5 showing switching of the magnetizations in the FIG.
6 2 modification of the magnetic recording medium and
7 a previously proposed magnetic recording medium;

8 FIG. 5 is a diagram showing a portion of a
9 recording surface of a patterned medium on an
10 enlarged scale;

11 FIG. 6 is a cross-sectional view showing
12 the main parts of one embodiment of a magnetic
13 storage apparatus according to the present
14 invention; and

15 FIG. 7 is a plan view showing the main
16 parts of the magnetic storage apparatus shown in FIG.
17 6.

18 DESCRIPTION OF THE PREFERRED EMBODIMENTS

19 FIG. 1 is a cross-sectional view showing
20 the main parts of one embodiment of a magnetic
21 recording medium according to the present invention.
22 A magnetic recording medium 10 shown in FIG. 1
23 includes a non-magnetic substrate 11, a seed layer
24 12, an underlayer 13, a non-magnetic intermediate
25 layer 14, a first magnetic layer 15, a non-magnetic
26 coupling layer 16, a second magnetic layer 17, and a
27 protection layer 18 which are successively stacked
28 in this order. The magnetic recording medium 10 can
29 be produced by sputtering, for example. A lubricant
30 layer 19 may further be provided on top of the
31 protection layer 18.

32 The non-magnetic substrate 11 is made of
33 for example, Al, glass or Si. The non-magnetic
34 substrate 11 may be mechanically textured, if
35 desired, but such texturing is not required.

36 The seed layer 12 may be made of NiP or
37 NiAl, for example, but the seed layer 12 is

1 preferably made of NiP, for example, especially in
2 the case where the non-magnetic substrate 11 is made
3 of Al or an Al alloy. The seed layer 12 may or may
4 not be oxidized, and may or may not be mechanically
5 textured. The seed layer 12 may be made of a B2
6 structure alloy such as NiAl and FeAl when the non-
7 magnetic substrate 11 is made of glass, for example.
8 The seed layer 12 is provided to promote a (001) or
9 (112) texture of the underlayer 13 which is formed
10 on the seed layer 12. The underlayer 13 may be made
11 of Cr or a Cr alloy, similarly as in the case of a
12 conventional magnetic recording medium.

13 In a case where the magnetic recording
14 medium 10 is a magnetic disk, the mechanical
15 texturing provided on the non-magnetic substrate 11
16 or the seed layer 12 which is made of NiP is made in
17 a circumferential direction of the magnetic disk,
18 that is, in the direction in which the tracks of the
19 magnetic disk extend.

20 The non-magnetic intermediate layer 14 is
21 provided to further promote epitaxy, narrow the
22 grain distribution of the first magnetic layer 15,
23 and orient the anisotropy axes (axes of easy
24 magnetization) of the first magnetic layer 15 along
25 a plane parallel to the recording surface of the
26 magnetic recording medium 10. The non-magnetic
27 intermediate layer 14 is made of an hcp structure
28 alloy such as CoCr-M, where M = B, Mo, Nb, Ta, W, Cu
29 or alloys thereof, and has a thickness in a range of
30 1 to 5 nm.

31 The first magnetic layer 15 is made of a
32 material such as Co, Ni, Fe, Co alloy, Ni alloy or
33 the like. In other words, Co alloys such as CoCr,
34 CoCrTa, CoCrPt and CoCrPt-M, where M = B, Mo, Nb, Ta,
35 W, Cu or alloys thereof, may be used for the first
36 magnetic layer 15. Especially when using a Co alloy
37 for the first magnetic layer 15, the Co
38 concentration of the Co alloy may be set high, that

1 is, the Co alloy may be Co rich, so as to increase
2 the exchange coupling magnetic field (hereinafter
3 simply referred to as an exchange coupling field),
4 which will be described later. The first magnetic
5 layer 15 preferably has a thickness in the range of
6 2 to 30 nm, for example.

7 The non-magnetic coupling layer 16 is made
8 of a material such as Ru, Rh, Re, Ir, Cr, Cu, Ru
9 alloy, Rh alloy, Re alloy, Ir alloy, Cr alloy, Cu
10 alloy or alloys thereof. For example, when the non-
11 magnetic coupling layer 16 is made of Ru, the non-
12 magnetic coupling layer 16 has a thickness in the
13 range of 0.4 to 1.0 nm, and desirably has a
14 thickness on the order of approximately 0.8 nm. For
15 this particular thickness range of the non-magnetic
16 coupling layer 16, the magnetizations of the first
17 magnetic layer 15 and the second magnetic layer 17
18 (which will be described later) are antiparallel.

19 The second magnetic layer 17 is made of a
20 material such as Co or a Co alloy such as CoCr,
21 CoCrTa, CoCrPt, CoCrPt-M, where M = B, Mo, Nb, Ta, W,
22 Cu or alloys thereof. Especially when using a Co
23 alloy for the second magnetic layer 17, the Co
24 concentration of the Co alloy may be set high, that
25 is, the Co alloy may be Co rich, so as to make the
26 exchange coupling field large. For example, the
27 second magnetic layer 17 preferably has a thickness
28 in the range of 2 to 30 nm. Of course, the layer
29 structure of the second magnetic layer 17 is not
30 limited to a single-layer structure, and the second
31 magnetic layer 17 may employ a multi-layer structure.

32 The protection layer 18 may be made of C,
33 for example. In addition, the lubricant layer 19 is
34 preferably made of an organic lubricant, for example,
35 for use with a magnetic transducer such as a spin-
36 valve head. The protection layer 18 and the
37 lubricant layer 19 form a protection layer structure

1 at the recording surface of the magnetic recording
2 medium 10.

3 Obviously, the layer structure under the
4 exchange layer structure is not limited to that
5 shown in FIG. 1. For example, the underlayer 13 may
6 be made of Cr or a Cr alloy and formed to a
7 thickness in the range of 5 to 40 nm on the non-
8 magnetic substrate 11, and the first magnetic layer
9 15 may be provided on this underlayer 13. In
10 addition, although the first and second magnetic
11 layers 15 and 17 having the antiparallel
12 magnetizations are respectively formed by one
13 magnetic layer each in this embodiment, it is
14 possible, for example, to additionally provide under
15 the first magnetic layer 15 one or more magnetic
16 layers having antiparallel magnetization with
17 respect to an adjacent magnetic layer. In this case,
18 an exchange coupling field H_{ex} of each additionally
19 provided magnetic layer is set larger than a
20 coercivity H_{c2} of the second magnetic layer 17, so
21 that the magnetizations (magnetization directions)
22 of each additionally provided magnetic layer rotate
23 together with the first and second magnetic layers
24 15 and 17.

25 The magnetic recording medium 10 having
26 the basic structure described above is characterized
27 in that the first and second magnetic layers 15 and
28 17 maintain the antiparallel magnetization states at
29 the time of recording, and the magnetization
30 directions of the first and second magnetic layers
31 15 and 17 rotate together. For this reason, it is
32 desirable that the recording magnetic field
33 (hereinafter simply referred to as a recording
34 field) that is applied to the magnetic recording
35 medium 10 is in a range that does not create a
36 switching magnetic field (hereinafter simply
37 referred to as a switching field) H_{sw^*} that acts to
38 switch the magnetization of the first magnetic layer

1 15 to become parallel to the magnetization of the
2 second magnetic layer 17. The position of the
3 switching field H_{sw}^* can be found from a coercivity
4 H_{c1} of the first magnetic layer 15 and an exchange
5 coupling field Hex_1 of the first magnetic layer 15
6 which is generated by the exchange coupling of the
7 first and second magnetic layers 15 and 17, as will
8 be described later in more detail.

9 The exchange coupling field Hex is the
10 field which is generated by the exchange coupling of
11 the first and second magnetic layers 15 and 17.
12 Generally, the exchange coupling field Hex_1 of the
13 first magnetic layer 15 can be obtained from $Hex_1 = J/t_1 M_{s1}$, where J denotes an exchange coupling
14 constant, t_1 denotes a thickness of the first
15 magnetic layer 15, and M_{s1} denotes a magnetization
16 of the first magnetic layer 15. Similarly, an
17 exchange coupling field Hex_2 of the second magnetic
18 layer 17 can be obtained from $Hex_2 = J/t_2 M_{s2}$, where
19 J denotes the exchange coupling constant, t_2 denotes
20 a thickness of the second magnetic layer 17, and M_{s2}
21 denotes a magnetization of the second magnetic layer
22 17. In this specification, a description will be
23 given by focusing on the exchange coupling field
24 Hex_1 generated in the first magnetic layer 15.

25 When the exchange coupling field Hex_1 is
26 set to be larger than both the coercivity H_{c1} of the
27 first magnetic layer 15 and the coercivity H_{c2} of
28 the second magnetic layer 17, it is possible to make
29 the magnetizations of the first and second magnetic
30 layers 15 and 17 mutually antiparallel. In addition,
31 because the desired switching field H_{sw}^* can be
32 obtained from the sum of the exchange coupling field
33 Hex_1 and the coercivity H_{c1} of the first magnetic
34 layer 15, as will be described later, it is possible
35 to carry out the recording while maintaining the
36 magnetizations of the first and second magnetic
37 layers 15 and 17 in an antiparallel state by

1 applying on the magnetic recording medium 10 a
2 recording field which does not reach the level of
3 the switching field H_{sw^*} .

4 Furthermore, when the coercivity H_{c1} of
5 the first magnetic layer 15 is set to be large, the
6 difference between the coercivity H_{c2} of the second
7 magnetic layer 17 and the switching field H_{sw^*} can
8 be made large, to thereby enable an increased degree
9 of freedom of design of the magnetic recording
10 medium 10.

11 In this specification, the switching field
12 H_{sw^*} refers to the field which switches the
13 magnetization of the first magnetic layer 15 to
14 become parallel to the magnetization of the second
15 magnetic layer 17 when an external field is applied
16 to the magnetic recording medium 10 while increasing
17 the field strength, in a state where the coercivity
18 H_{c2} of the second magnetic layer 17 is smaller than
19 the exchange coupling field H_{ex1} .

20 Next, a more detailed description will be
21 given of the characterizing structures described
22 above which are included in the magnetic recording
23 medium 10.

24 In this embodiment, the coercivity H_{c2} of
25 the second magnetic layer 17 is set to approximately
26 4 kOe, and the coercivity H_{c1} of the first magnetic
27 layer 15 is set to approximately 0.5 kOe, for
28 example. Hence, the coercivity H_{c2} of the second
29 magnetic layer 17 is sufficiently large compared to
30 the coercivity H_{c1} of the first magnetic layer 15.

31 The magnetization and thickness product
32 t_2M_{s2} of the second magnetic layer 17 is set to be
33 larger than the magnetization and thickness product
34 t_1M_{s1} of the first magnetic layer 15. For this
35 reason, the difference that is obtained by
36 subtracting the magnetization and thickness product
37 t_1M_{s1} of the first magnetic layer 15 from the
38 magnetization and thickness product t_2M_{s2} of the

1 second magnetic layer 17 mainly contributes to the
2 signal at the time of the reproduction. In addition,
3 since the magnetization and thickness product $t_1 M_{s1}$
4 of the first magnetic layer 15 is set to be small,
5 the exchange coupling field H_{ex1} can be made large,
6 because $H_{ex1} = J/t_1 M_{s1}$ as described above.

7 Furthermore, in the magnetic recording
8 medium 10 of this embodiment, it is desirable to
9 provide a coupling intensifying region for
10 intensifying the exchange coupling strength between
11 the second magnetic layer 17 and the first magnetic
12 layer 15, in addition to the basic structure shown
13 in FIG. 1.

14 FIG. 2 is an enlarged cross-sectional view
15 showing a portion of a modification of the FIG. 1
16 embodiment of the magnetic recording medium 10 that
17 includes the coupling intensifying region. More
18 particularly, FIG. 2 shows the layer structure of
19 the part of this modification of the magnetic
20 recording medium 10, including a coupling
21 intensifying region provided between the non-
22 magnetic coupling layer 16 and the first and second
23 magnetic layers 15 and 17.

24 In the layer structure shown in FIG. 2, a
25 lower coupling intensifying region 21 is provided
26 between the first magnetic layer 15 and the non-
27 magnetic coupling layer 16, and an upper coupling
28 intensifying region 22 is provided between the non-
29 magnetic coupling layer 16 and the second magnetic
30 layer 17. However, it is not essential to provide
31 both the upper and lower coupling intensifying
32 regions 21 and 22, and only one of the upper and
33 lower coupling intensifying regions 21 and 22 may be
34 provided. The magnetization of the lower coupling
35 intensifying region 21 is parallel to the
36 magnetization of the first magnetic layer 15, and
37 the magnetization of the upper coupling intensifying
38 region 22 is parallel to the magnetization of the

1 second magnetic layer 17. The lower coupling
2 intensifying region 21, together with the first
3 magnetic layer 15, has a function of intensifying
4 the exchange coupling between the first and second
5 magnetic layers 15 and 17. Similarly, the upper
6 coupling intensifying region 22, together with the
7 second magnetic layer 17, has a function of
8 intensifying the exchange coupling between the first
9 and second magnetic layers 15 and 17. The exchange
10 coupling between the first and second magnetic
11 layers 15 and 17 can be intensified even when only
12 one of the upper and lower coupling intensifying
13 regions 22 and 21 is provided.

14 The lower coupling intensifying region 21
15 may be formed as a portion of either the first
16 magnetic layer 15 or the non-magnetic coupling layer
17 16, or it may be formed as an interface on the
18 surface of the first magnetic layer 15 or on the
19 non-magnetic coupling layer 16. In addition, the
20 lower coupling intensifying region 21 may be formed
21 as a full layer with a relatively uniform thickness
22 or it may be formed as a series of projections.
23 Similarly, the upper coupling intensifying region 22
24 may be formed as a portion of either the second
25 magnetic layer 17 or the non-magnetic coupling layer
26 16, or it may be formed as an interface on the
27 surface of the second magnetic layer 17 or the non-
28 magnetic coupling layer 16. Further, the upper
29 coupling intensifying region 22 may be formed as a
30 full layer with a relatively uniform thickness or it
31 may be formed as a series of projections.

32 The upper and lower coupling intensifying
33 regions 22 and 21 are preferably made of Fe, Co, Ni
34 or alloys thereof. It is particularly desirable to
35 use materials such as Co, CoCr and CoCrTa for the
36 upper and lower coupling intensifying regions 22 and
37 21. Moreover, the upper and lower coupling
38 intensifying regions 22 and 21 may also be made of

1 Co-X, CoCr-Y or CoCrTa-Y, where X = Pt, Ta, B, Cu, W,
2 Mo, Nb, Ru, Rh, Ir or alloys thereof, and Y = Pt, B,
3 Cu, W, Mo, Nb, Ru, Rh, Ir or alloys thereof.

4 It is desirable that the maximum thickness
5 of the material forming each of the upper and lower
6 coupling intensifying regions 22 and 21 is limited
7 to approximately 2 nm. In addition, the material
8 forming each of the upper and lower coupling
9 intensifying regions 22 and 21 may exist in a
10 surface state or in a dispersed state. For example,
11 the function of intensifying the exchange coupling
12 strength is sufficiently displayed even in a state
13 where a desired material used is dispersed in a
14 granular state within or on the surface of the first
15 magnetic layer 15, for example. Accordingly, even
16 in a state where only a small amount of the desired
17 material is dispersed within or on the surface of
18 the first magnetic layer 15, for example, the
19 dispersed material as a whole can sufficiently
20 function as a coupling intensifying region.

21 The thickness of the desired material
22 within each of the upper and lower coupling
23 intensifying regions 22 and 21 is approximately 2.0
24 nm or less. Because the characteristics required of
25 the magnetic recording medium 10 change depending on
26 the material that is used to form the upper and
27 lower coupling intensifying regions 22 and 21, it is
28 desirable to determine the thickness of the material
29 forming each of the upper and lower coupling
30 intensifying regions 22 and 21 by taking such
31 factors into consideration.

32 The materials such as Fe, Co, Ni and
33 alloys thereof, which are suited for forming the
34 upper and lower coupling intensifying regions 22 and
35 21, may also be used to form the first and second
36 magnetic layers 15 and 17. Hence, the composition
37 of the material forming the upper and lower coupling
38 intensifying regions 22 and 21 may be the same as,

1 or similar to, the composition of the material
2 forming the upper and lower magnetic layers 15 and
3 17. However, it is desirable that the material
4 forming the upper and lower coupling intensifying
5 regions 22 and 21 is richer in Co (or the like)
6 compared to the material forming the first and
7 second magnetic layers 15 and 17. For example,
8 compared to materials which include Co and are
9 generally used to form a magnetic layer, it is
10 desirable that the Co-content of the material
11 forming the upper and lower coupling intensifying
12 regions 22 and 21 is at least 10 at% to 20 at%
13 richer. Therefore, even in a case where materials
14 having similar compositions are used for the upper
15 and lower coupling intensifying regions 22 and 21
16 and the first and second magnetic layers 15 and 17,
17 the upper and lower coupling intensifying regions 22
18 and 21 are Co rich compared to the first and second
19 magnetic layers 15 and 17.

20 The materials described above which are
21 rich in Co (or the like) may also be used to form
22 the first and second magnetic layers 15 and 17. In
23 this case, the lower coupling intensifying region 21
24 is included in the first magnetic layer 15, and the
25 surface of the first magnetic layer 15 (that is, the
26 interface between the first magnetic layer 15 and
27 the non-magnetic coupling layer 16) substantially
28 corresponds to the lower coupling intensifying
29 region 21. In addition, the upper coupling
30 intensifying region 22 is included in the second
31 magnetic layer 17, and the surface of the second
32 magnetic layer 17 (that is, the interface between
33 the second magnetic layer 17 and the non-magnetic
34 coupling layer 16) substantially corresponds to the
35 upper coupling intensifying region 22. Hence, it is
36 unnecessary in this case to prepare a material for
37 separately forming the upper and lower coupling
38 intensifying regions 22 and 21.

1 Accordingly, the lower coupling
2 intensifying region 21 simply needs to exist
3 substantially at a boundary of the first magnetic
4 layer 15 and the non-magnetic coupling layer 16, and
5 the upper coupling intensifying region 22 simply
6 needs to exist substantially at a boundary of the
7 second magnetic layer 17 and the non-magnetic
8 coupling layer 16.

9 In this modification, the upper and lower
10 coupling intensifying regions 22 and 21 are
11 preferably respectively made of Co having a
12 thickness of 1 nm. By employing the layer structure
13 which includes the upper and lower coupling
14 intensifying regions 22 and 21, the exchange
15 coupling strength between the first and second
16 magnetic layers 15 and 17 is increased. In addition,
17 among the coercivity H_{c2} of the second magnetic
18 layer 17, the coercivity H_{c1} of the first magnetic
19 layer 15 and the exchange coupling field H_{ex1} of the
20 first magnetic layer 15, both the coercivities H_{c1}
21 and H_{c2} are smaller than the exchange coupling field
22 H_{ex1} . According to this layer structure, the
23 coercivity H_{c12} is naturally smaller than the
24 switching field H_{sw^*} .

25 FIG. 3 is a diagram showing a hysteresis
26 loop of the FIG. 2 modification of the magnetic
27 recording medium 10. More particularly, FIG. 3
28 shows the hysteresis loop in which the abscissa
29 indicates the field and the ordinate indicates the
30 Kerr signal due to the Kerr effect. It should be
31 noted that the hysteresis loop of the FIG. 1
32 embodiment will be of a similar shape to that shown
33 in FIG. 3, except that the various parameters will
34 be somewhat shifted.

35 Arrows ST1 through ST4 indicated in the
36 upper part of FIG. 3 respectively indicate
37 magnetization states (i.e., the states of the
38 direction of magnetization) of the first and second

1 magnetic layers 15 and 17. The hysteresis loop
2 shown in FIG. 3 includes a main hysteresis loop MAR
3 at a central portion, and a sub-hysteresis loop SUR
4 on both the right and left portions.

5 The large main hysteresis loop MAR is
6 shown for a case where the magnetizations of the
7 first and second magnetic layers 15 and 17 rotate
8 together while maintaining the antiparallel state,
9 that is, for a case where the state ST2 and the
10 state ST3 are repeated.

11 On the other hand, the small sub-
12 hysteresis loop SUR on the right shows a case where
13 the magnetization of the first magnetic layer 15
14 switches from the antiparallel state to the parallel
15 state with respect to the magnetization of the
16 second magnetic layer 17, and vice versa. In FIG. 3,
17 γ indicates a position of the switching field H_{sw}^*
18 where the magnetization of the first magnetic layer
19 switches from the antiparallel state to the parallel
20 state with respect to the magnetization of the
21 second magnetic layer 17.

22 The sub-hysteresis loop SUR may be
23 regarded as a hysteresis loop (minor loop)
24 indicating the magnetization state of the first
25 magnetic layer 15. In other words, when a field is
26 applied in a positive direction (+10 kOe) from a
27 state (residual magnetization state) indicated by δ ,
28 the sub-hysteresis loop SUR passes the position γ
29 and follows SUR-1 on the right side. In this state,
30 the magnetization of the first magnetic layer 15
31 switches from the state ST3, which is antiparallel
32 to the magnetization of the second magnetic layer 17,
33 to the state ST4, which is parallel to the
34 magnetization of the second magnetic layer 17. On
35 the other hand, when the field is reduced from the
36 state ST4 (i.e., is reduced by 10 kOe), the sub-
37 hysteresis loop SUR follows SUR-2 on the left side.
38 In this state, the magnetization of the first

1 magnetic layer 15 switches from the state ST4 which
2 is parallel to the magnetization of the second
3 magnetic layer 17 to the state ST3 which is
4 antiparallel to the magnetization of the second
5 magnetic layer 17.

6 Therefore, as may be seen from FIG. 3, the
7 magnetizations of the first and second magnetic
8 layers 15 and 17 can be maintained in the
9 antiparallel state when the recording field is
10 applied in a range of the main hysteresis loop MAR
11 in which the applied field is smaller than the
12 switching field H_{sw^*} , as indicated by γ .

13 The approximate center of the sub-
14 hysteresis loop SUR indicates the exchange coupling
15 field H_{ex1} of the first magnetic layer 15. In
16 addition, in the main hysteresis loop MAR, β
17 indicates the strength of the field which rotates
18 the magnetizations while maintaining the
19 magnetizations of the first and second magnetic
20 layers 15 and 17 antiparallel. The strength β
21 approximately corresponds to the coercivity H_{c2} of
22 the second magnetic layer 17.

23 The conditions for rotating the
24 magnetizations of the first and second magnetic
25 layers 15 and 17 together while maintaining the
26 magnetizations of the first and second magnetic
27 layers 15 and 17 antiparallel are that at least the
28 coercivity H_{c2} of the second magnetic layer 17 is
29 smaller than the exchange coupling field H_{ex1} of the
30 first magnetic layer 15, and that the field applied
31 to the magnetic recording medium 10 is not larger
32 than the switching field H_{sw^*} .

33 Since the sub-hysteresis loop SUR may be
34 regarded as indicating the magnetization state of
35 the first magnetic layer 15 as described above, a
36 difference between the exchange coupling field H_{ex1}
37 of the first magnetic layer 15 and the switching
38 field H_{sw^*} may be regarded as the coercivity H_{c1} of

1 the first magnetic layer 15. Hence, the switching
2 field H_{sw^*} is equal to the sum of the exchange
3 coupling field H_{ex1} and the coercivity H_{c1} of the
4 first magnetic layer 15 ($H_{sw^*} = H_{ex1} + H_{c1}$).

5 In the particular case shown in FIG. 3,
6 the coercivity H_{c2} of the second magnetic layer 17
7 satisfies the condition $H_{c2} < H_{ex1}$, and naturally,
8 $H_{c2} < (H_{ex1} + H_{c1})$, and $H_{c2} < H_{sw^*}$. In this case,
9 the position of the switching field H_{sw^*} can be
10 prescribed by use of the exchange coupling field
11 H_{ex1} and the coercivity H_{c1} of the first magnetic
12 layer 15, and used when designing the magnetic
13 recording medium 10.

14 By using a recording field within the
15 range MT shown in FIG. 3, which satisfies the
16 relationship $H_{c2} < H_{sw^*}$, it is possible to carry out
17 the recording on the magnetic recording medium 10
18 while maintaining the magnetizations of the first
19 and second magnetic layers 15 and 17 in the
20 antiparallel state.

21 Although the description above is given
22 with respect to the sub-hysteresis loop SUR on the
23 right in FIG. 3, the sub-hysteresis loop on the left
24 is approximately symmetrical, with respect to the
25 origin, to the loop on the right. Accordingly, a
26 description of the sub-hysteresis loop on the left
27 will be omitted in this specification.

28 Next, a more detailed description will be
29 given of the hysteresis loop shown in FIG. 3 with
30 reference to numerical values. In this modification
31 of the magnetic recording medium 10, the coupling
32 intensifying regions 21 and 22 are provided to
33 intensify the exchange coupling of the first and
34 second magnetic layers 15 and 17. Accordingly, the
35 exchange coupling field H_{ex} between the first and
36 second magnetic layers 15 and 17 is improved to
37 approximately 5 kOe, and the switching field H_{sw^*} is
38 approximately 5.5 kOe.

1 The exchange coupling field Hex1 of the
2 first magnetic layer 15 is set to be larger than the
3 coercivity Hc2 of the second magnetic layer 17, and
4 the coercivity Hc2 of the second magnetic layer 17
5 and the switching field Hsw* satisfy the
6 relationship $Hc2 < Hsw^*$.

7 When the above described relationships are
8 satisfied, it is possible to always maintain the
9 magnetizations of the first and second magnetic
10 layers 15 and 17 in the antiparallel state while a
11 recording field is applied from a residual
12 magnetization state indicated by α and the
13 switching of the magnetizations occurs as indicated
14 by β in FIG. 3. In other words, in the state α
15 (the residual magnetization state), the
16 magnetizations of the first and second magnetic
17 layers 15 and 17 are in the antiparallel state ST2,
18 but when a recording field is applied in a direction
19 opposite to the magnetization of the second magnetic
20 layer 17, the magnetization of the second magnetic
21 layer 17 switches to the state ST3, approximately at
22 the position indicated by β , when the recording
23 field becomes larger than the coercivity Hc2 of the
24 second magnetic layer 17.

25 In this case, the coercivity Hc2 of the
26 second magnetic layer 17 and the exchange coupling
27 field Hex1 of the first magnetic layer 15 satisfy
28 the relationship $Hc2 < Hex1$. For this reason, the
29 first magnetic layer 15 is strongly coupled to the
30 second magnetic layer 17, and the magnetization of
31 the first magnetic layer 15 switches simultaneously
32 with the magnetization of the second magnetic layer
33 17, while the magnetizations of the first and second
34 magnetic layers 15 and 17 are maintained
35 antiparallel. This antiparallel state of the
36 magnetizations of the first and second magnetic
37 layers 15 and 17 is maintained in the residual
38 magnetization state, that is, at the position

1 indicated by δ , where the recording field becomes
2 zero.

3 In other words, in the above described
4 state where the magnetizations of the first and
5 second magnetic layers 15 and 17 are maintained
6 antiparallel, the exchange coupling strength (or
7 force) which acts to maintain the magnetizations of
8 the first and second magnetic layers 15 and 17
9 antiparallel is larger than the external recording
10 field which is applied to the magnetic recording
11 medium 10.

12 FIGS. 4A and 4B, respectively, are
13 diagrams showing switching of the magnetizations in
14 the present invention of the magnetic recording
15 medium 10 and a previously proposed magnetic
16 recording medium which has been proposed in U.S.
17 Patent Application S.N.09/425,788 described above.

18 In the case of the present magnetic
19 recording medium 10, the switching process is
20 completed by switching of the magnetizations once by
21 a predetermined recording field from state I to
22 state III or vice versa, as shown in FIG. 4A.

23 But in the case of the previously proposed
24 magnetic recording medium, the switching of the
25 state I to the state III can only be realized via a
26 state II in which the magnetization of the
27 ferromagnetic layer corresponding to the first
28 magnetic layer 15 is parallel to the magnetization
29 of the magnetic layer corresponding to the second
30 magnetic layer 17. In other words, a transition
31 from state I to state II and another transition from
32 state II to state III are required in order to
33 realize the switching from state I to state III, and
34 a transition from state III to state II and another
35 transition from state II to state I are required in
36 order to realize the switching from state III to
37 state I.

1 Therefore, as may be seen from a
2 comparison of FIGS. 4A and 4B, the present magnetic
3 recording medium 10 can realize a higher speed of
4 recording as compared with the previously proposed
5 magnetic recording medium because of the high-speed
6 switching of the magnetizations directly from state
7 I to state III, and vice versa.

8 In the present invention, the coupling
9 intensifying region is used to further improve the
10 exchange coupling between the first and second
11 magnetic layers 15 and 17. However, the exchange
12 coupling strength between the first and second
13 magnetic layers 15 and 17 may also be adjusted by
14 altering the state of the interface of the material
15 forming the non-magnetic coupling layer 16. For
16 example, the exchange coupling strength between the
17 first and second magnetic layers 15 and 17 may be
18 adjusted by altering the interface state of Ru which
19 forms the non-magnetic coupling layer 16. In
20 addition, the exchange coupling strength between the
21 first and second magnetic layers 15 and 17 may also
22 be adjusted and increased by altering the
23 composition and the thickness of each of the first
24 and second magnetic layers 15 and 17, by altering
25 the state of the magnetic grains of each of the
26 first and second magnetic layers 15 and 17, or by
27 improving the smoothness of the Ru interface or the
28 like between the non-magnetic coupling layer 16 and
29 the first magnetic layer 15 and/or the second
30 magnetic layer 17. More particularly, the exchange
31 coupling strength between the first and second
32 magnetic layers 15 and 17 may be increased by
33 decreasing the thickness of the first magnetic layer
34 15 and/or the second magnetic layer 17, by
35 increasing the Co-content (or the Co concentration)
36 of the first magnetic layer 15 and/or the second
37 magnetic layer 17, or by increasing the magnetic

1 grain size of the first magnetic layer 15 and/or the
2 second magnetic layer 17.

3 On the other hand, the above described
4 relationship between the coercivity H_{c2} of the
5 second magnetic layer 17 and the exchange coupling
6 field H_{ex1} of the first magnetic layer 15 may be
7 maintained, without changing the exchange coupling
8 strength (that is, maintaining the exchange coupling
9 strength approximately constant), by decreasing the
10 coercivity H_{c2} of the second magnetic layer 17.
11 More particularly, the coercivity H_{c2} of the second
12 magnetic layer 17 may be adjusted by changing the
13 material, the additives and the production process
14 of the second magnetic layer 17, so as to change the
15 microstructure, the crystal structure and the
16 magnetic domain structure. For example, when
17 forming the second magnetic layer 17 from CoCrPtB,
18 it is possible to decrease the coercivity H_{c2} by
19 suppressing the Pt-content of CoCrPtB.

20 Furthermore, increasing the coercivity H_{c1}
21 of the first magnetic layer 15 is also one method of
22 satisfying the relationship $H_{c2} < H_{ex1} + H_{c1}$.
23 However, if the coercivity H_{c1} is increased
24 excessively, there are cases where it is no longer
25 possible to maintain the antiparallel state of the
26 magnetizations of the first and second magnetic
27 layers 15 and 17 in the residual magnetization state.
28 Accordingly, it is also necessary to design the
29 coercivity H_{c1} to be smaller than the exchange
30 coupling field H_{ex1} .

31 One important aspect of the magnetic
32 recording medium 10 of both the FIG. 1 embodiment
33 and the FIG. 2 modification is that the
34 magnetizations of the first and second magnetic
35 layers 15 and 17 are switched, while still
36 maintaining the magnetizations of the first and
37 second magnetic layers 15 and 17 antiparallel, by
38 applying a recording field to the medium 10 that is

1 larger than the coercivity H_{c2} , and by using various
2 methods to control the exchange coupling field H_{e1}
3 of the first magnetic layer 15, the coercivity H_{c2}
4 of the second magnetic layer and the coercivity H_{c1}
5 of the first magnetic layer 15. In addition, the
6 recording field that is applied to the magnetic
7 recording medium 10 also needs to be smaller than
8 the switching field H_{sw^*} . As a result, it is
9 possible to carry out a high-speed switching process
10 that switches the magnetizations of the first and
11 second magnetic layers 15 and 17 while maintaining
12 the magnetizations of the first and second magnetic
13 layers 15 and 17 antiparallel.

14 As may be seen from FIG. 3, if the
15 recording field applied to the magnetic recording
16 medium 10 is large when compared to the switching
17 field H_{sw^*} , the magnetization of the first magnetic
18 layer 15 becomes parallel to the magnetization of
19 the second magnetic layer 17, which is not desirable.
20 Accordingly, the maximum value of the recording
21 field should be larger than the coercivity H_{c2} of
22 the second magnetic layer 17, but smaller than the
23 switching field H_{sw^*} , that is, the maximum recording
24 field should be set to be within a range between β
25 and γ in FIG. 3. In other words, it is desirable
26 that the maximum value of the recording field from
27 the recording head does not exceed the switching
28 field H_{sw^*} .

29 Therefore, by controlling the coercivity
30 H_{c2} of the second magnetic layer 17 and the exchange
31 coupling field H_{e1} of the first magnetic layer 15
32 so as to satisfy the relationship $H_{c2} < H_{e1}$ and by
33 keeping the recording field from the recording head
34 from exceeding the switching field H_{sw^*} , it is
35 possible to switch the magnetizations of the first
36 and second magnetic layers 15 and 17 while
37 maintaining these magnetizations antiparallel.
38 Unlike the previously proposed magnetic recording

1 medium described above, in the present invention,
2 state II, in which the magnetizations of the first
3 and second magnetic layers 15 and 17 become parallel,
4 does not exist during the recording process, and for
5 this reason, the present invention can realize
6 high-speed recording. The deterioration of the non-
7 linear transition shift (NLTS) due to the causes
8 described above will thus not occur in the present
9 invention. In addition, normal reproduction is
10 possible even when high-speed reproduction is
11 carried out immediately after recording.

12 FIG. 5 is a diagram showing a portion of a
13 recording surface of a so-called patterned medium on
14 an enlarged scale. The patterned medium 30 shown in
15 FIG. 5 has a storage capacity per unit area several
16 times greater than those of a conventional magnetic
17 recording media. Unlike the structures of the
18 conventional magnetic recording media, the patterned
19 medium 30 has unit recording portions 31 which are
20 artificially designed as micro-magnetic recording
21 regions that are formed by a lithography technique,
22 or the like. Boundaries of adjacent unit recording
23 portions 31 are separated on the recording surface
24 of the patterned medium 30 to thereby realize low
25 noise. Hence, it is unnecessary to use an additive
26 such as Cr to promote segregation and grain size
27 reduction. For this reason, the magnetic layer may
28 be made of a material having a small additive
29 content and a large Co-content (Co concentration).
30 That is, it is possible to use a material that can
31 obtain a large exchange coupling. As a result, it
32 is possible to easily satisfy the following
33 relationship of the exchange coupling field H_{ex1} of
34 the first magnetic layer 15, in which the exchange
35 coupling field H_{ex1} is larger than the coercivities
36 H_{c1} and H_{c2} of the first and second magnetic layers
37 15 and 17.

1 In another embodiment of the magnetic
2 recording medium according to the present invention,
3 the present invention is applied to the patterned
4 medium 30 described above. More particularly, in
5 this embodiment, each unit recording portion 31 has
6 a stacked structure which includes at least the
7 first magnetic layer 15, the non-magnetic coupling
8 layer 16 and the second magnetic layer 17 which
9 satisfy the relationships of the FIG. 1 embodiment
10 and the FIG. 2 modification described above.
11 According to this embodiment, it is possible to
12 realize a magnetic recording medium which has a high
13 recording density which is further improved and can
14 carry out high-speed recording and reproduction
15 which is also further improved.

16 In the embodiments and the modification
17 described above, the first magnetic layer 15, the
18 non-magnetic coupling layer 16 and the second
19 magnetic layer 17 are stacked in this order above
20 the non-magnetic substrate 11. However, it is of
21 course possible to stack the second magnetic layer
22 17, the non-magnetic coupling layer 16 and the first
23 magnetic layer 15 in this order above the non-
24 magnetic substrate 11. However, in general, it is
25 desirable to arrange the magnetic layer which
26 dominates the recording on the side of the magnetic
27 recording medium that is closer to the head.

28 Next, a description will be given of an
29 embodiment of a magnetic storage apparatus according
30 to the present invention by referring to FIGS. 6 and
31 7. FIG. 6 is a cross-sectional view showing the
32 basic parts of this embodiment of the magnetic
33 storage apparatus according to the present invention,
34 and FIG. 7 is a plan view of the magnetic storage
35 apparatus shown in FIG. 6.

36 As shown in FIGS. 6 and 7, the magnetic
37 storage apparatus 40 generally includes a housing 43.
38 A motor 44, a hub 45, a plurality of magnetic

1 recording media 46, a plurality of recording and
2 reproducing heads 47, a plurality of suspensions 48,
3 a plurality of arms 49, and an actuator unit 41 are
4 all provided within the housing 43. The magnetic
5 recording media 46 are mounted on the hub 45 which
6 is rotated by the motor 44. Each recording and
7 reproducing head 47 is mounted on the tip end of a
8 corresponding arm 49 via the suspension 48. The
9 arms 49 are moved by the actuator unit 41. The
10 basic construction of this magnetic storage
11 apparatus is known, and a detailed description
12 thereof will be omitted in this specification.

13 This embodiment of the magnetic storage
14 apparatus is characterized by the magnetic recording
15 media 46. Each magnetic recording medium 46 has the
16 structure of any of the embodiments and the
17 modification of the magnetic recording medium
18 described above in conjunction with FIGS. 1 through
19 5. In addition, the recording field that is applied
20 to the magnetic recording medium 46 from the
21 recording head of the recording and reproducing head
22 47 is controlled to be both larger than the
23 coercivity H_{c2} of the second magnetic layer of the
24 magnetic recording medium 46 and smaller than the
25 switching field H_{sw^*} . Of course, the number of
26 magnetic recording media 46 is not limited to three,
27 and for example, one, two, four or more magnetic
28 recording media 46 may be provided.

29 The basic construction of the magnetic
30 storage apparatus is not limited to that shown in
31 FIGS. 6 and 7. In addition, the magnetic recording
32 medium used in the present invention is not limited
33 to a magnetic disk.

34 Further, the present invention is not
35 limited to these embodiments, but various variations
36 and modifications may be made without departing from
37 the scope of the present invention.